Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Green and Sustainable Chemistry

Anthropogenic-driven perturbations on nitrogen cycles and interactions with climate changes

Cheng Gong[1], Sian Kou-Giesbrecht[2] and Sönke Zaehle[1]

Abstract

Anthropogenic activities have substantially perturbed the global nitrogen (N) cycle directly through enhancing reactive N (Nr) inputs and indirectly through climate and land-use change. However, the climatic impacts of the N cycle and its feedbacks on climate change remain very uncertain. In this review, we provide an overview of the dominant pathways by which anthropogenic Nr affects the climate system and summarize the available scientific assessments. We also review the latest progress on the responses of N cycle to changing climate to understand the potential for feedbacks between the N cycle and climate. With the urgent need to reduce Nr in the future to alleviate its negative environmental impacts, e.g. air pollution and eutrophication, we highlight the importance for bridging disciplines of atmospheric chemistry, ecology, and climatology to improve the scientific understanding and develop cobenefits for both environmental protection and climate change mitigation.

Addresses

[1] Max Planck Institute for Biogeochemistry, Jena, Germany
[2] Department of Earth and Environmental Sciences, Dalhousie University, Halifax, NS, Canada

Corresponding author: Gong, Cheng (cgong@bgc-jena.mpg.de)

Current Opinion in Green and Sustainable Chemistry 2024, **46:**100897

This review comes from a themed issue on **Chemistry for Climate (2024)**

Edited by **Borhane Mahjoub**

Available online 22 February 2024

For complete overview of the section, please refer the article collection - Chemistry for Climate (2024)

https://doi.org/10.1016/j.cogsc.2024.100897

Keywords

Anthropogenic nitrogen, Biogeochemistry–climate interactions, Climate effects of anthropogenic nitrogen, Terrestrial carbon–nitrogen interactions, Atmospheric nitrogen chemistry, Ammonium and nitrate aerosols, Nitrogen cycles under climate changes.

Introduction

Nitrogen (N) constitutes nearly 78% of the atmosphere; however, nearly 99% of atmospheric N is gas-phase molecular N (N_2) [1]. Two processes in the natural environment, i.e. biological nitrogen fixation (BNF) and lightning, can break the triple bond of N_2 and thereby create reactive nitrogen (Nr). As one of the most important nutrients for living organisms supporting biosynthesis, growth, maintenance, and propagation, Nr can be subjected to a vast number of chemical and biochemical reactions and functions through its importance in enzyme synthesis and biomolecules [2,3]. However, Nr entering marine and terrestrial ecosystems may also be exported out of the biosphere and be emitted to the atmosphere, where it interferes with the radiative transfer in the atmosphere through tropospheric chemical reactions of greenhouse gases and aerosols [4,5]. As a result, anthropogenic Nr plays important roles in the global biogeochemical cycles (of carbon, nitrogen, phosphorus, etc.), further influencing environmental health [6,7], ecosystem biodiversity [8], and climate changes [9].

Fossil fuel combustion and N fixation technology (e.g. the Haber–Bosch reaction) have introduced large quantities of anthropogenic Nr to the Earth system since the beginning of the industrial revolution (around 1750). The scale of this perturbation has grown exponentially since the beginning of the industrial revolution and, in current decades, is estimated to be on par with or even exceed natural Nr generation through BNF and lightning [10]. Excessive Nr, on the one hand, substantially affects climate. For instance, increased nitrous oxide (N_2O) concentrations and ammonium (NH_4^+)/nitrate (NO_3^-) aerosol loadings in the atmosphere could warm and cool the atmosphere through the greenhouse effect and solar-radiation diffusion, respectively [11]. The enhanced Nr inputs into ecosystems through N deposition and fertilizer and manure application may alleviate global warming by increasing ecosystem carbon sequestration [12,13]. Furthermore, short-lived nitrogen oxides (NO_x) play vital roles in atmospheric chemistry and non-linearly alter atmospheric greenhouse gases of ozone (O_3) [14] and methane (CH_4) [15]. On the other hand, climate change induced by anthropogenic greenhouse gases also substantially affects almost all of the natural N processes [16,17], with the possibility of causing feedbacks to climate. The net climate effects of anthropogenic Nr as well as the N climate feedbacks, although understood in principle, are challenging to quantify and therefore remain purely constrained.

The importance of interactions between N dynamics and climate has gained recognition in the past decades [9,16,18]. Substantial efforts have been dedicated in the past years to improve the scientific understanding through field experiments, meta-data analysis, machine-learning techniques, and model simulations. In this review study, we aim to give an overview on previous studies, most of which have predominantly focused on specific N compounds or processes within the global N cycles, and integrate the latest key findings with respect to interactions of N cycles and climate change. As illustrated in Figure 1, we will firstly overview the pathways that N cycles influence climate and identify the contributions led by direct anthropogenic Nr inputs (Section Main climate-affecting N compounds), then we will briefly demonstrate the recent discoveries of key N-cycle processe responses to changing climate as well as the anthropogenic perturbations (Section Climate feedbacks due to perturbated N cycle). Finally, we will conclude and outline future perspectives in Section Concluding remarks.

Main climate-affecting N compounds

N_2O

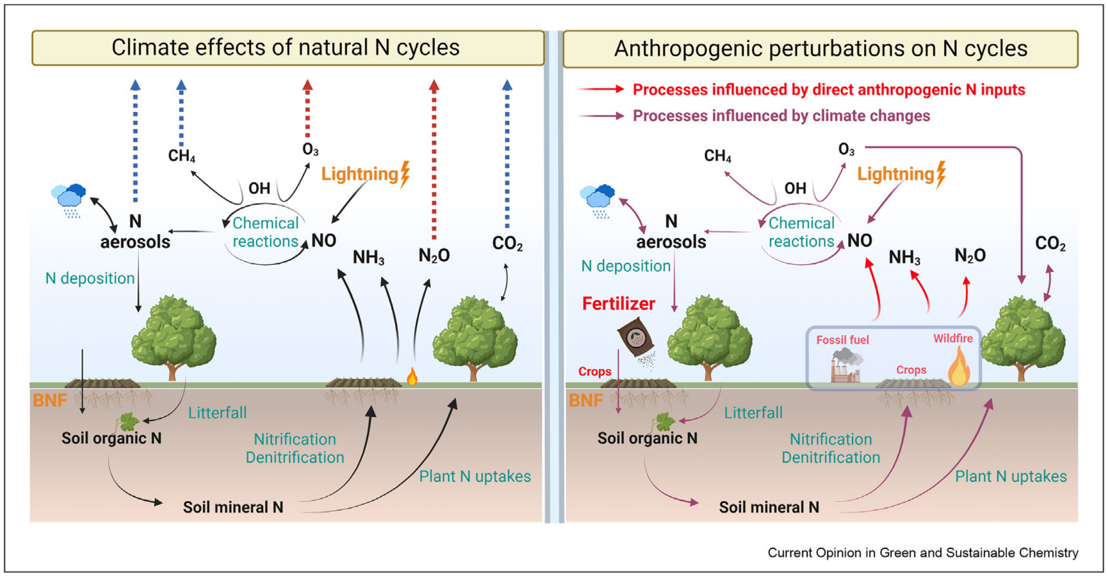
N_2O is a long-lived greenhouse gas with a global warming potential that is about 273 times greater than that of CO_2 per unit mass over a period of 100 years. IPCC AR6 reported with high confidence that atmospheric N_2O mole fractions have risen from 270 ppb in 1750 to 331 ppb in 2019 and have contributed to $+0.21 \pm 0.03$ W m^{-2} effective radiative forcing (ERF) relative to the preindustrial period [19]. Increases in agricultural fertilizer/manure application, N deposition, and fossil fuel combustions were identified as primary drivers behind this increase of N_2O [20], but the exact attribution of anthropogenic contributions to the N_2O increases is still challenging. Anthropogenic sources during 2007–2016 were estimated to be 7.3 [4.2–11.4] Tg N yr^{-1} among the global total 17.0 Tg N yr^{-1} emissions [21]. Limited but also challenging flux measurements [22–24], uncertain and dynamic spatiotemporal distributions of N fertilizer application, and agricultural land uses [25], as well as imperfections in model representations [26] together are the main cause for this large range.

N-species aerosols

Aerosols remain in the troposphere for a timescale of days to weeks. Most compounds result in a cooling effect on climate as they scatter solar radiation and interact with cloud formation and lifetime. Ammonium (NH_4^+) and nitrate (NO_3^-) are the two dominant N-species aerosols. It is well-known that the major source of ammonia (NH_3), which is the primary precursor to generate NH_4^+, is from agricultural activities [27], but significant gaps remain in quantifying global NH_3 emissions. Recent bottom-up estimates assessed global agricultural NH_3 emissions at about 58 Tg N yr^{-1} in 2010 [28], whereas the top-down inversion accounting for natural and other anthropogenic NH_3 sources suggested global emissions from 90 to 191 Tg N yr^{-1} [29,30]. Some studies also showed current emission inventories tended to underestimate NH_3 emissions particularly in hotspot regions, such as Western Europe [31] and Eastern China [32]. With uncertainties in NH_3 emissions, the ERF of NH_4^+ in 2014 was estimated to be about -0.07 W m^{-2}, based on ensemble means of earth system models [11].

Emissions of nitrogen oxide (NO_x), which is the main precursor of NO_3^-, are dominated by fossil fuel sources [27]. Both bottom-up and top-down estimates showed consistently similar magnitudes and decadal trends in

Figure 1



Current Opinion in Green and Sustainable Chemistry

The climate effects of Nr compounds (left) also with anthropogenic-driven perturbations on N cycles (right). For each panel, the left part indicates the Nr inputs to the terrestrial ecosystem, whereas the right part indicates the Nr fluxes to the atmosphere. The blue or red dashed arrows on the top of the left panel indicate the cooling or warming effects of each component on climate, respectively. Abbreviation: Nr = reactive nitrogen.

anthropogenic NO_x emissions [33–35]. NO_x engages in numerous chemical reactions and significantly perturbates atmospheric hydroxyl radical (OH) concentrations (see below Section NO_x indirect effects through atmospheric chemical reactions). The non-linearity of atmospheric chemistry introduces uncertainties in the global burden, spatial distribution, as well as the particle sizes of NO_3^-, all of which are essential to quantify the NO_3^- climate effects. Therefore, estimates of the cooling effects of NO_3^- through solar diffusion varied from very small (~-0.025 $W\ m^{-2}$) to more substantial effects ($-0.14\ W\ m^{-2}$) [11,36–39]. The interactions between NO_3^- aerosols and cloud remained quite uncertain, with radiative forcing assessed by a limited number of studies ranging from -0.05 to $-0.22\ W\ m^{-2}$ [40–42].

NO_x indirect effects through atmospheric chemical reactions

As the highly reactive gas, NO_x is involved in various chemical reactions with other green-house gases, in particular, O_3 and CH_4. It thereby affects climate indirectly by changing the lifetime and thus the atmospheric burden of these gases. In general, increased atmospheric NO_x concentrations will lead to higher OH concentrations, further increasing O_3 concentrations [14] while, at the same time, shortening CH_4 lifetime and thereby reducing CH_4 concentrations [15]. A recent assessment based on an ensemble of Earth System models showed that NO_x-induced O_3 enhancement warmed the climate by $+0.2 \pm 0.07\ W\ m^{-2}$, whereas the reduced CH_4 lifetime led by NO_x contributed a cooling effect of about $-0.2\ W\ m^{-2}$ to $-0.37\ W\ m^{-2}$ until 2014 since pre-industrial times [11]. The complexity of OH chemical dynamics and non-linear interactions among NO_x, volatile organic compounds, and O_3 is the primary cause for the uncertainty in this quantification.

C–N interactions in terrestrial ecosystems

The majority of the N element in the terrestrial ecosystem constitutes plants and microbes in organic forms and plays crucial roles in enzyme-mediated processes. However, the available N for plants is normally in the forms of dissolved inorganic N, such as ammonium or nitrate ions, which is mineralized from soil organic N by microbial activities [43]. Meanwhile, soil microbes also regulate BNF levels, thereby influencing the overall N availability for plants [44]. A portion of the mineralized inorganic N will be lost from the terrestrial ecosystem as gases phase though nitrification and denitrification [26], or as dissolved forms through leaching [45].

Next to phosphorus, the N in terrestrial ecosystems is one of the most important nutrients for plants and microbial organisms. It is essential for C assimilation, growth, and maintenance and thereby tightly connected to the C cycle. The N limitation of biomass production is generally believed to be strong in natural temperate and boreal forests [46], attenuating the expected increases in carbon storage due to CO_2 fertilization of plant photosynthesis under future climate change [47]. Anthropogenic-driven increases in N fertilizer application and atmospheric Nr deposition can increase productivity by lifting N limitation. Synthesis of available data from ecosystem manipulation experiments by meta-analysis or machine learning has revealed responses of terrestrial C sinks to N addition, ranging from 1 kg C $(kg\ N)^{-1}$ to 25 kg C $(kg\ N)^{-1}$ depending on different land cover types and amounts and types of N addition [13,48–50].

Terrestrial biosphere models (TBMs) integrate process understanding of biogeochemical cycles at large scales and are another useful tool to quantify the climate effects of N-induced increases in C sequestration [3]. For instance, Zaehle et al. [51] attributed a cumulative cooling effect of about $-0.1\ W\ m^{-2}$ to Nr-induced carbon storage in the terrestrial biosphere since pre-industrial times by applying a TBM to reproduce global observed trends of atmospheric CO_2. In recent years, dynamic C–N coupling has been induced in an increasing number of TBMs [52–55]. These models generally agree with earlier findings, but evaluation against independent benchmark highlights remaining uncertainty and a formidable challenge to further constrain model uncertainties to better quantify the N effects on terrestrial carbon sinks and the resulting climate impacts [53] (Figure 2).

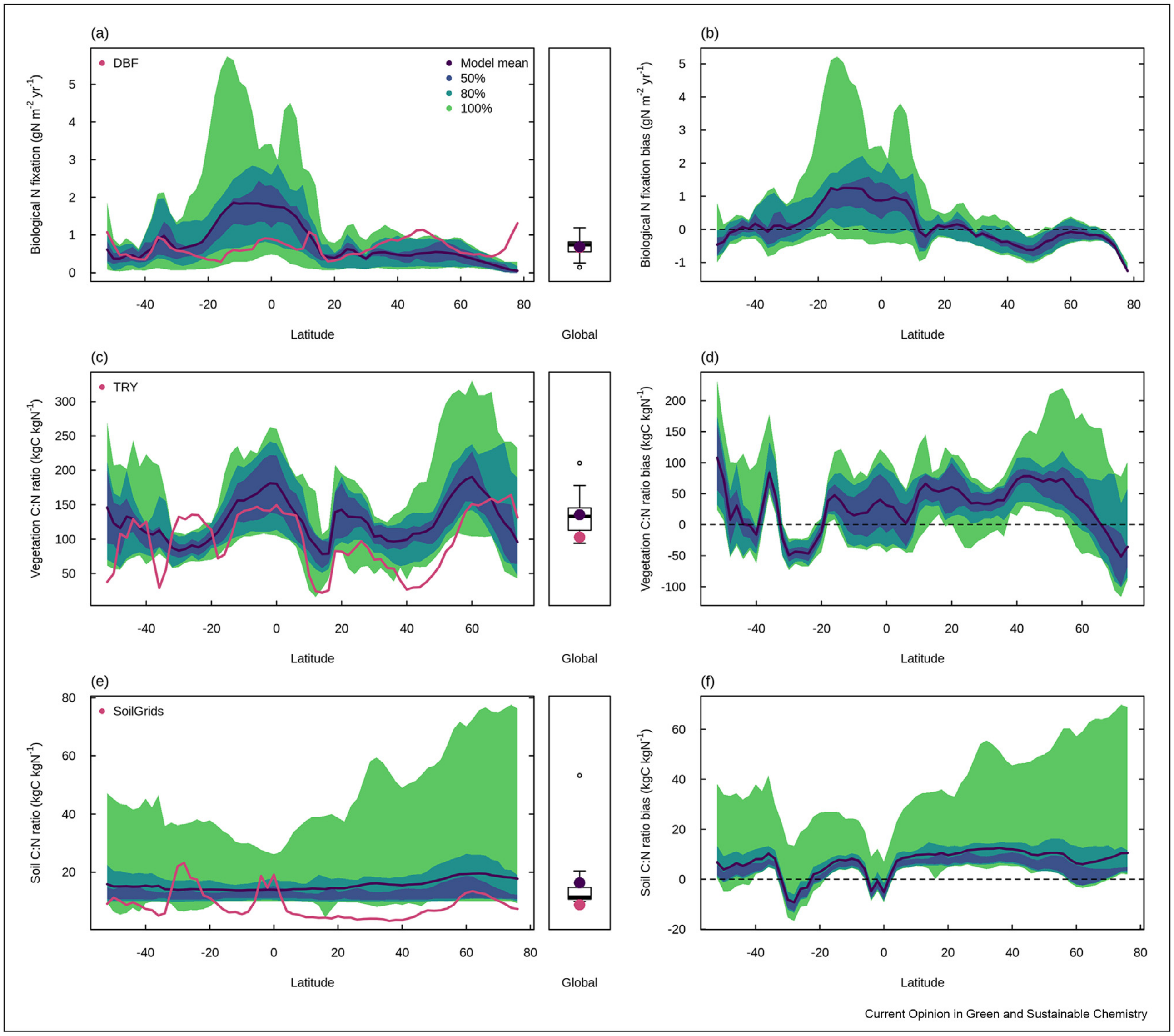
Other Nr-related climate effects

There are additional, less well-quantified pathways of Nr known to affect climate, which are summarized here: (1) Nr-induced increases in aerosols and O_3 could influence terrestrial carbon sinks by reducing ratios of direct to diffuse photosynthetically active radiation [57,58] and by damaging leaf photosynthesis [59–61], respectively. (2) Nr inputs into terrestrial ecosystems may reduce soil CH_4 uptake [48,62] and thus increase atmospheric CH_4. However, soil CH_4 uptake plays only a small role in the global CH_4 cycle, and the magnitude of the Nr effects ranges from −60% to +10% [63]. (3) Riverine and marine N_2O emissions and the C–N interactions might also be influential on climate. Yao et al. [64] suggested that increased N inputs enhanced riverine emissions of N_2O from $70.4 \pm 15.4\ Gg\ N\ yr^{-1}$ in 1900 to $291.3 \pm 58.6\ Gg\ N\ yr^{-1}$ in 2016, whereas marine N deposition is estimated to contribute to present-day marine N_2O emissions by about 0.01–0.32 $Tg\ N\ yr^{-1}$ [19], and the marine primary productivity by 0.3 Pg C yr^{-1} increases [2] but with neglectable changes in the resultant air–sea CO_2 fluxes [65].

The net climate effects of anthropogenic Nr

Quantifying the net climate effects of anthropogenic Nr requires crossing different time scales and disciplines

Figure 2



Current Opinion in Green and Sustainable Chemistry

Latitudinal distributions and global means of BNF, vegetation C: N ratio, and soil C: N ratio simulated by the TRENDY-N ensemble (averaged across models over 1980–2021) in comparison to observations. Panels (**a, c, e**) show the latitudinal distribution of the mean, and boxplots show the global mean. Panels (**b, d, f**) show the latitudinal distribution of the bias. Latitudinal distributions show the mean (black line) and the 50 %, 80 %, and 100% percentiles across models. Boxplots show the median, interquartile range (box), and 80% percentiles (whiskers) across models. Observation-based datasets are from Davies-Barnard and Friedlingstein [56] for biological N fixation, the TRY plant trait database for vegetation C:N ratio, and SoilGrids for soil C:N ratio. This figure is from Kou-Giesbrecht et al. [53]. Abbreviations: BNF = biological nitrogen fixation; TRY (TRY—not an acronym; Kattge et al., 2011 [107]).

among atmospheric chemistry, climate dynamics, and ecological science. To date, this gap among different scientific communities and quantifications is typically bridge in a ‘puzzle-style’ framework, wherein climate effects (e.g. radiative forcing) or key parameters (e.g. terrestrial C responses to N addition; N_2O emission factors) from previous independent studies are combined to generate a ‘best estimate’ of anthropogenic Nr climate effects. Table 1 summarized the four most recent and comprehensive estimates to our knowledge, covering the U.S., Europe, China, and globe. To improve our understanding of the Nr imprint of anthropogenic Nr on climate, it is important to (1) address remaining uncertainties in the underlying regional to global emission databases for all Nr species and improve consistency between emission categories; (2) integrate process-understanding to derive non-linear response functions of ecosystems to reduce the dependency of the assessments on linear approximations; and (3) appropriately deal with the evaluation of climate

Table 1

Summary of present-day climate effects of anthropogenic Nr. The uncertainty ranges of each estimate were indicated by standard deviation (±) or square brackets depending on each individual study.

	Erisman et al. [9]	Pinder et al. [66]	Butterbach-Bahl et al. [67]	Shi et al. [68]
Region	Global	U.S.	Europe	China
Metrics	Radiative forcing	GWP20/GWP100	Radiative forcing[a]	GWP20/GWP100
Units	W m^{-2}	Tg eCO$_2$	W m^{-2}	Tg eCO$_2$
N$_2$O	+0.16	+314 [+202, +428]/ +291 [+180, +395]	0.017	345 ± 19/311 ± 17
Nr-related aerosols	−0.38	−36.67 [−8.18, −103.5]/0	−0.0165	−156 ± 45/-0.12 ± 0.13
NOx effects on CH$_4$ lifetime		−271 [−177.4, −385]/ −7.19 [0, −15.64]	−0.0046	−349.8 ± 155.6/-13.2 ± 7.6
NOx effects on O$_3$	+0.13		0.0029	
N-induced terrestrial carbon sinks	−0.2	−206.8 [−134.65, −292.4]/ −155.02 [−98.96, −236.76]	−0.019 (excluding agricultural fertilization)	−49.9 ± 54.7/-86.2 ± 39.7
Other effects	+0.05	[+66 + 140]	0.0453	111 ± 100/111 ± 100
Net climate effects	−0.24 [−0.5 + 0.2]	−200.47 [−299.6, +17.6]/ +128.79 [+112.2, +317.1]	−0.0173	−100 ± 414/322 ± 163

Abbreviation: Nr = reactive nitrogen.

[a] The values indicated the global radiative forcing induced by emissions in Europe.

impact by accounting for regional and global short-lived as well as long-lived climate forcers.

Climate feedbacks due to perturbated N cycle

Besides direct anthropogenic Nr inputs, anthropogenic-driven climate change substantially alters the global N cycle, which in turn results in feedback effects on climate. Here, we provide a brief overview of key findings in the past years covering changes in ecosystem N cycles and atmospheric Nr-related chemistry and extrapolate the potential climate feedbacks.

Responses of ecosystem N cycling to climate changes

A number of processes in the terrestrial N cycle are substantially influenced by climate changes through the responses of enzyme activities, microbial species, and strategy [69]. Firstly, the BNF, the major natural source of Nr, is responding to temperature with new emerging evidence to better quantify the optimal temperature for BNF and its thermal acclimation to growth temperature [70,71]. Secondly, increased temperature accelerates the decay of organic material, which enhances inorganic N cycling in the soil and thereby enhance terrestrial carbon storage [72,73]. The intensification of inorganic N cycles can not only lead to a positive N$_2$O-warming feedback [74] but also intensify the soil emissions of NH$_3$ [75] and NO$_x$ [76]. These processes may be particularly relevant in permafrost regions and peatlands, which are even more sensitive to global warming due to arctic amplification. Recent studies have demonstrated that the increases in mineralized N with permafrost thawing failed to enhance the N availability of plants due to increased N demands and higher N-gas loss [77–79]. Thirdly, the simultaneous changes in multiple environmental factors, e.g. elevated CO$_2$ concentrations, warming, and changes in soil moisture, may enhance the strength of N limitation on terrestrial C uptake [80,81]. Last but not the least, land use changes and increased ecosystem disturbance (e.g. wildfire) may also deeply alter the whole ecosystem N cycle [82–84]. For example, the expansion of agricultural land may lead to higher N fertilizer application [85], whereas strategically intercropping of N-fixing crops (e.g. grain legumes) and cereals may alleviate such issues by improving N-use efficiency [86]. Meanwhile, more frequent wildfire under the changing climate accelerates the turnover rates of terrestrial N into the atmosphere, generating varied Nr-related gases and particles and substantially feeding back to the climate [87,88]. Overall, although specific components of the Nr-related feedbacks have been studied, a comprehensive and quantitative overview of the likely effects on future climate–biogeochemical feedbacks, such as N availability for the carbon cycle, is still lacking [19].

Responses of atmospheric Nr-related chemistry to climate changes

Higher temperatures in general not only accelerate reaction rates in atmospheric chemistry but also exert significant non-linear influences on individual reactions.

Clear evidence supports the hypothesis that higher temperature could accelerate evaporation of ammonium nitrate and thereby reduce Nr-related aerosol loadings [89]. Current Earth System models in general reported positive sensitivities of lightning NO_x emissions to the warmer climate [90], while insignificant or even negative sensitivities were reported in other studies [91,92]. The NO_x effects on CH_4 and O_3 with warming is strongly dependent on changes in global OH concentrations and distributions and therefore is subject to significant uncertainties [93,94].

Concluding remarks

In this review, we firstly summarized the known pathways in which Nr impacts climate. Recent findings underscored the vital roles of the N cycles in affecting global climate; however, each pathway was still associated with uncertainty. In particular, two major challenges of (1) improving estimates in global soil emissions of Nr gases (N_2O, NH_3, and NO_x) and (2) reducing uncertainties in atmospheric OH chemistry and associated NO_x effects on aerosols, O_3, and CH_4 substantially impede a more comprehensive understanding of the climatic effects of anthropogenic Nr. To fill this knowledge gap, on the one hand, long-term continuous observations of soil Nr-gas fluxes, especially for short-lived NH_3 and NO_x, and improved understandings in microbial dynamics with soil ammonification, nitrification, and denitrification (e.g. Ref. [95]) are both essential. On the other hand, new chemical mechanisms revealed from smog chambers (e.g. Ref. [96]), field campaigns (e.g. Ref. [97]), and the constraints by satellite retrievals (e.g. Ref. [98,99]) could promote a better description in global OH chemistry. Last but not the least, comprehensive Earth system models, which represent process-based terrestrial and marine N biogeochemical cycles, atmospheric chemical reactions, radiative transfer, and climate dynamics, which would be crucial to comprehensively reveal climate effects of anthropogenic Nr as well as the potential climate feedbacks through N cycles.

We further overviewed the latest progresses on the effects of anthropogenic perturbations on global N cycles. While the direct anthropogenic Nr addition into soil (e.g. via fertilizer application and N deposition) or atmosphere (e.g. via fossil fuel combustion) has been widely studied, the effects of indirect pathways, such as N processes influenced by changing climate, elevated CO_2, land-use changes, intensified wildfire, and diverse agricultural management strategies, remained inadequately understood. In-depth manipulating experiments in crucial zones, including tropical rainforest [100], permafrost [101], and agricultural lands [102], with as many N-cycle variables are urgently required. On the other hand, some national or regional practices have indicated that improved human management on both forests and croplands holds promise in mitigating ecosystem disturbances (e.g. wildfire) [103], and increasing N use efficiency [104]. Those practices could increase Nr sequestration in the terrestrial plants and soil, thereby alleviating the environmental pollution led by anthropogenic Nr. For instance, the extensively practiced crop rotation, in particular over South Asia, with more N-fixing crops is effective in reducing Nr loss and increasing crop yields with less fertilizer application [105,106]. Nevertheless, it is still unknown how climate will respond to the efforts of reducing anthropogenic Nr. It is urgently required to bridge knowledge gaps among communities of agricultural nutrition, global biogeochemical science, atmospheric chemistry, and climate dynamics to achieve win—win in both environmental protection and climate change mitigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgement

C.G. and S.Z. acknowledge support from the European Commission H2020 programme (Grant-No. 101003536; ESM2025).

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest
** of outstanding interest

1. Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB, *et al.*: **The nitrogen cascade**. *Bioscience* 2003, **53**: 341–356.
2. Duce RA, LaRoche J, Altieri K, Arrigo KR, Baker AR, Capone DG, *et al.*: **Impacts of atmospheric anthropogenic nitrogen on the open ocean**. *Science* 2008, **320**:893–897.
3. Zaehle S, Dalmonech D: **Carbon-nitrogen interactions on land at global scales: current understanding in modelling climate biosphere feedbacks**. *Curr Opin Environ Sustain* 2011, **3**: 311–320.
4. Derwent RG, Stevenson DS, Doherty RM, Collins WJ, Sanderson MG, Johnson CE: **Radiative forcing from surface NOx emissions: spatial and seasonal variations**. *Climatic Change* 2008, **88**:385–401.
5. Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE: **Improved attribution of climate forcing to emissions**. *Science* 2009, **326**:716–718.
6. de Vries W: **Impacts of nitrogen emissions on ecosystems and human health: a mini review**. *Curr Opn Environ Sci Health* 2021:21.
7. Nieder R, Benbi DK: **Reactive nitrogen compounds and their influence on human health: an overview**. *Rev Environ Health* 2022, **37**:229–246.

8. Bobbink R, Hicks K, Galloway J, Spranger T, Alkemade R, Ashmore M, *et al.*: **Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis**. *Ecol Appl* 2010, **20**:30–59.

9. * Erisman JW, Galloway J, Seitzinger S, Bleeker A, Butterbach-Bahl K: **Reactive nitrogen in the environment and its effect on climate change**. *Curr Opin Environ Sustain* 2011, **3**:281–290.

The only estimates to our knowledge that assessed the global climate effects of anthropogenic reactive nitrogen.

10. * Fowler D, Coyle M, Skiba U, Sutton MA, Cape JN, Reis S, *et al.*: *The global nitrogen cycle in the twenty-first century*. Philosophical Transactions of the Royal Society B-Biological Sciences; 2013: 368.

A comprehensive review study that went through each process in N cycles and provided the estimates of global N budget.

11. ** Thornhill GD, Collins WJ, Kramer RJ, Olivi D, Skeie RB, O'Connor FM, *et al.*: **Effective radiative forcing from emissions of reactive gases and aerosols - a multi-model comparison**. *Atmos Chem Phys* 2021, **21**:853–874.

This study summarized the current understanding gained from ensembles of earth system models for the radiative forcing of atmospheric components (including Nr-related gases and aerosols)

12. Lessmann M, Ros GH, Young MD, de Vries W: **Global variation in soil carbon sequestration potential through improved cropland management**. *Global Change Biol* 2022, **28**: 1162–1177.

13. Schulte-Uebbing LF, Ros GH, de Vries W: **Experimental evidence shows minor contribution of nitrogen deposition to global forest carbon sequestration**. *Global Change Biol* 2022, **28**:899–917.

14. Lu X, Ye XP, Zhou M, Zhao YH, Weng HJ, Kong H, *et al.*: **The underappreciated role of agricultural soil nitrogen oxide emissions in ozone pollution regulation in North China**. *Nat Commun* 2021, **12**.

15. Peng SS, Lin X, Thompson RL, Xi Y, Liu G, Hauglustaine D, *et al.*: **Wetland emission and atmospheric sink changes explain methane growth in 2020**. *Nature* 2022, **612**:477.

16. ** Fowler D, Steadman CE, Stevenson D, Coyle M, Rees RM, Skiba UM, *et al.*: **Effects of global change during the 21st century on the nitrogen cycle**. *Atmos Chem Phys* 2015, **15**: 13849–13893.

A comprehensive review study that summarized all known influences of climate changes on global N cycles.

17. Greaver TL, Clark CM, Compton JE, Vallano D, Talhelm AF, Weaver CP, *et al.*: **Key ecological responses to nitrogen are altered by climate change**. *Nat Clim Change* 2016, **6**:836–843.

18. Altieri KE, Fawcett SE, Hastings MG: **Reactive nitrogen cycling in the atmosphere and ocean**. In Jeanloz R, Freeman KH, Eds., *Annual review of earth and planetary sciences*, vol. 49; 2021: 523–550. 49, 2021.

19. Canadell JG, Monteiro PMS, Costa MH, Cunha LCd, Cox PM, Eliseev AV, *et al.*: **Global carbon and other biogeochemical cycles and feedbacks**. In *Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*; 2021:673–816.

20. Tian HQ, Yang J, Xu RT, Lu CQ, Canadell JG, Davidson EA, *et al.*: **Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: magnitude, attribution, and uncertainty**. *Global Change Biol* 2019, **25**:640–659.

21. ** Tian HQ, Xu RT, Canadell JG, Thompson RL, Winiwarter W, Suntharalingam P, *et al.*: **A comprehensive quantification of global nitrous oxide sources and sinks**. *Nature* 2020, **586**. 248-+.

The most comprehensive study that estimated the global N_2O budget.

22. Barton L, Wolf B, Rowlings D, Scheer C, Kiese R, Grace P, *et al.*: **Sampling frequency affects estimates of annual nitrous oxide fluxes**. *Sci Rep* 2015, **5**.

23. Liao JQ, Huang YY, Li ZL, Niu SL: **Data-driven modeling on the global annual soil nitrous oxide emissions: spatial pattern and attributes**. *Sci Total Environ* 2023:903.

24. Wang QH, Zhou F, Shang ZY, Ciais P, Winiwarter W, Jackson RB, *et al.*: **Data-driven estimates of global nitrous oxide emissions from croplands**. *Natl Sci Rev* 2020, **7**: 441–452.

25. Lu CQ, Tian HQ: **Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance**. *Earth Syst Sci Data* 2017, **9**:181–192.

26. Feng MY, Peng SS, Wang YL, Ciais P, Goll DS, Chang JF, *et al.*: **Overestimated nitrogen loss from denitrification for natural terrestrial ecosystems in CMIP6 Earth System Models**. *Nat Commun* 2023:14.

27. Hoesly RM, Smith SJ, Feng LY, Klimont Z, Janssens-Maenhout G, Pitkanen T, *et al.*: **Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS)**. *Geosci Model Dev (GMD)* 2018, **11**:369–408.

28. * Liu L, Xu W, Lu XK, Zhong BQ, Guo YX, Lu X, *et al.*: **Exploring global changes in agricultural ammonia emissions and their contribution to nitrogen deposition since 1980**. In *Proceedings of the National Academy of Sciences of the United States of America*; 2022:119.

This study give a robust bottom-up estimates of global agricultural NH_3 emissions

29. Evangeliou N, Balkanski Y, Eckhardt S, Cozic A, Van Damme M, Coheur PF, *et al.*: **10-year satellite-constrained fluxes of ammonia improve performance of chemistry transport models**. *Atmos Chem Phys* 2021, **21**:4431–4451.

30. Luo Z, Zhang Y, Chen W, Van Damme M, Coheur PF, Clarisse L: **Estimating global ammonia (NH3) emissions based on IASI observations from 2008 to 2018**. *Atmos Chem Phys* 2022, **22**: 10375–10388.

31. Cao HS, Henze DK, Zhu LY, Shephard MW, Cady-Pereira K, Dammers E, *et al.*: **4D-Var inversion of European NH_3 emissions using CrIS NH_3 measurements and GEOS-chem adjoint with Bi-directional and uni-directional flux schemes**. *J Geophys Res Atmos* 2022:127.

32. Kong L, Tang X, Zhu J, Wang ZF, Pan YP, Wu HJ, *et al.*: **Improved inversion of monthly ammonia emissions in China based on the Chinese ammonia monitoring network and ensemble kalman filter**. *Environ Sci Technol* 2019, **53**:12529–12538.

33. Ding J, Miyazaki K, van der ARJ, Mijling B, Kurokawa JI, Cho S, *et al.*: **Intercomparison of NOx emission inventories over east asia**. *Atmos Chem Phys* 2017, **17**:10125–10141.

34. Jena C, Ghude SD, Beig G, Chate DM, Kumar R, Pfister GG, *et al.*: **Inter-comparison of different NOX emission inventories and associated variation in simulated surface ozone in Indian region**. *Atmos Environ* 2015, **117**:61–73.

35. McDuffie EE, Smith SJ, O'Rourke P, Tibrewal K, Venkataraman C, Marais EA, *et al.*: **A global anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific sources (1970-2017): an application of the Community Emissions Data System (CEDS)**. *Earth Syst Sci Data* 2020, **12**:3413–3442.

36. An Q, Zhang H, Wang ZL, Liu Y, Xie B, Liu QX, *et al.*: **The development of an atmospheric aerosol/chemistry-climate model, BCC_AGCM_CUACE2.0, and simulated effective radiative forcing of nitrate aerosols**. *J Adv Model Earth Syst* 2019, **11**:3816–3835.

37. Bian HS, Chin M, Hauglustaine DA, Schulz M, Myhre G, Bauer SE, *et al.*: **Investigation of global particulate nitrate from the AeroCom phase III experiment**. *Atmos Chem Phys* 2017, **17**:12911–12940.

38. Hauglustaine DA, Balkanski Y, Schulz M: **A global model simulation of present and future nitrate aerosols and their**

direct radiative forcing of climate. *Atmos Chem Phys* 2014, **14**: 11031–11063.

39. Zaveri RA, Easter RC, Singh B, Wang HL, Lu Z, Tilmes S, *et al.*: **Development and evaluation of chemistry-aerosol-climate model CAM5-chem-MAM7-MOSAIC: global atmospheric distribution and radiative effects of nitrate aerosol**. *J Adv Model Earth Syst* 2021, **13**.

40. Bellouin N, Rae J, Jones A, Johnson C, Haywood J, Boucher O: **Aerosol forcing in the climate model intercomparison project (CMIP5) simulations by HadGEM2-ES and the role of ammonium nitrate**. *J Geophys Res Atmos* 2011, **116**.

41. Lu Z, Liu X, Zaveri RA, Easter RC, Tilmes S, Emmons LK, *et al.*: **Radiative forcing of nitrate aerosols from 1975 to 2010 as simulated by MOSAIC module in CESM2-MAM4**. *J Geophys Res Atmos* 2021, **126**.

42. Xu L, Penner JE: **Global simulations of nitrate and ammonium aerosols and their radiative effects**. *Atmos Chem Phys* 2012, **12**:9479–9504.

43. Li ZL, Tian DS, Wang BX, Wang JS, Wang S, Chen HYH, *et al.*: **Microbes drive global soil nitrogen mineralization and availability**. *Global Change Biol* 2019, **25**:1078–1088.

44. Aasfar A, Bargaz A, Yaakoubi K, Hilali A, Bennis I, Zeroual Y, *et al.*: **Nitrogen fixing *azotobacter* species as potential soil biological enhancers for crop nutrition and yield stability**. *Front Microbiol* 2021:12.

45. Wang ZH, Li SX: **Nitrate N loss by leaching and surface runoff in agricultural land: a global issue (a review)**. In Sparks DL, Ed., *Advances in agronomy*, vol. 156; 2019:159–217.

46. Du EZ, Terrer C, Pellegrini AFA, Ahlstrom A, van Lissa CJ, Zhao X, *et al.*: **Global patterns of terrestrial nitrogen and phosphorus limitation**. *Nat Geosci* 2020, **13**. 221-+.

47. Terrer C, Jackson RB, Prentice IC, Keenan TF, Kaiser C, Vicca S, *et al.*: **Nitrogen and phosphorus constrain the CO2 fertilization of global plant biomass**. *Nat Clim Change* 2019, **9**. 684-+.

48. Liu LL, Greaver TL: **A review of nitrogen enrichment effects on three biogenic GHGs: the CO2 sink may be largely offset by stimulated N2O and CH4 emission**. *Ecol Lett* 2009, **12**: 1103–1117.

49. Liu YW, Piao SL, Makowski D, Ciais P, Gasser T, Song J, *et al.*: **Data-driven quantification of nitrogen enrichment impact on Northern Hemisphere plant biomass**. *Environ Res Lett* 2022, **17**.

50. Poulton P, Johnston J, Macdonald A, White R, Powlson D: **Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: evidence from long-term experiments at Rothamsted Research, United Kingdom**. *Global Change Biol* 2018, **24**:2563–2584.

51. Zaehle S, Ciais P, Friend AD, Prieur V: **Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions**. *Nat Geosci* 2011, **4**:601–605.

52. Davies-Barnard T, Meyerholt J, Zaehle S, Friedlingstein P, Brovkin V, Fan YC, *et al.*: **Nitrogen cycling in CMIP6 land surface models: progress and limitations**. *Biogeosciences* 2020, **17**:5129–5148.

53. ** Kou-Giesbrecht S, Arora VK, Seiler C, Arneth A, Falk S, Jain AK, *et al.*: **Evaluating nitrogen cycling in terrestrial biosphere models: a disconnect between the carbon and nitrogen cycles**. *Earth Syst. Dynam.* 2023, **14**:767–795.
The latest study that comprehensively assessed the performance of current terrestrial biosphere models in simulating global N cycles.

54. Wieder WR, Cleveland CC, Smith WK, Todd-Brown K: **Future productivity and carbon storage limited by terrestrial nutrient availability**. *Nat Geosci* 2015, **8**:441–444.

55. * Zaehle S, Medlyn BE, De Kauwe MG, Walker AP, Dietze MC, Hickler T, *et al.*: **Evaluation of 11 terrestrial carbon-nitrogen cycle models against observations from two temperate Free-Air CO2 Enrichment studies**. *New Phytol* 2014, **202**:803–822.
This study overviewed the C–N coupling in the terrestrial biosphere models.

56. Davies-Barnard T, Friedlingstein P: **The global distribution of biological nitrogen fixation in terrestrial natural ecosystems**. *Global Biogeochem Cycles* 2020, **34**.

57. Mercado LM, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M, *et al.*: **Impact of changes in diffuse radiation on the global land carbon sink**. *Nature* 2009, **458**. 1014-U87.

58. Zhou H, Yue X, Lei YD, Tian CG, Zhu J, Ma YM, *et al.*: **Distinguishing the impacts of natural and anthropogenic aerosols on global gross primary productivity through diffuse fertilization effect**. *Atmos Chem Phys* 2022, **22**: 693–709.

59. Franz M, Alonso R, Arneth A, Büker P, Elvira S, Gerosa G, *et al.*: **Evaluation of simulated ozone effects in forest ecosystems against biomass damage estimates from fumigation experiments**. *Biogeosciences* 2018, **15**:6941–6957.

60. Gong C, Yue X, Liao H, Ma YM: **A humidity-based exposure index representing ozone damage effects on vegetation**. *Environ Res Lett* 2021, **16**.

61. Sitch S, Cox PM, Collins WJ, Huntingford C: **Indirect radiative forcing of climate change through ozone effects on the land-carbon sink**. *Nature* 2007, **448**:791. U4.

62. Li Q, Peng CH, Zhang JB, Li YF, Song XZ: **Nitrogen addition decreases methane uptake caused by methanotroph and methanogen imbalances in a Moso bamboo forest**. *Sci Rep* 2021, **11**.

63. Xia N, Du EZ, Wu XH, Tang Y, Wang Y, de Vries W: **Effects of nitrogen addition on soil methane uptake in global forest biomes**. *Environ Pollut* 2020:264.

64. Yao YZ, Tian HQ, Shi H, Pan SF, Xu RT, Pan NQ, *et al.*: **Increased global nitrous oxide emissions from streams and rivers in the Anthropocene**. *Nat Clim Change* 2020, **10**. 138-+.

65. * Yamamoto A, Hajima T, Yamazaki D, Aita MN, Ito A, Kawamiya M: **Competing and accelerating effects of anthropogenic nutrient inputs on climate-driven changes in ocean carbon and oxygen cycles**. *Sci Adv* 2022, **8**.
This study investigated the Nr effects on ocean productivity as well as the air-ocean C fluxes.

66. Pinder RW, Davidson EA, Goodale CL, Greaver TL, Herrick JD, Liu LL: **Climate change impacts of US reactive nitrogen**. *Proc Natl Acad Sci USA* 2012, **109**:7671–7675.

67. Butterbach-Bahl K, Nemitz E, Zaehle S, Billen G, Boeckx P, Erisman JW, *et al.*: **Nitrogen as a threat to the European greenhouse balance**. In *The European nitrogen assessment: sources, effects and policy perspectives*. Edited by Bleeker A, Grizzetti B, Howard CM, Billen G, van Grinsven H, Erisman JW, *et al.*, Eds, Cambridge: Cambridge University Press; 2011: 434–462.

68. Shi YL, Cui SH, Ju XT, Cai ZC, Zhu YG: **Impacts of reactive nitrogen on climate change in China**. *Sci Rep* 2015, **5**.

69. Mattoo R, Suman BM: **Microbial roles in the terrestrial and aquatic nitrogen cycle-implications in climate change**. *FEMS Microbiol Lett* 2023:370.

70. Houlton BZ, Wang YP, Vitousek PM, Field CB: **A unifying framework for dinitrogen fixation in the terrestrial biosphere**. *Nature* 2008, **454**. 327-U34.

71. * Bytnerowicz TA, Akana PR, Griffin KL, Menge DNL: **Temperature sensitivity of woody nitrogen fixation across species and growing temperatures**. *Nat Plants* 2022, **8**. 209-+.
This study challenged the traditionall empirical relationships of BNF responses to increased temperature.

72. Kou-Giesbrecht S, Arora VK: **Compensatory effects between CO_2, nitrogen deposition, and nitrogen fertilization in terrestrial biosphere models without nitrogen compromise projections of the future terrestrial carbon sink**. *Geophys Res Lett* 2023:50.

73. Melillo JM, Butler S, Johnson J, Mohan J, Steudler P, Lux H, *et al.*: **Soil warming, carbon-nitrogen interactions, and forest carbon budgets**. *Proc Natl Acad Sci USA* 2011, **108**: 9508–9512.

74. Stocker TF, Qin D, Plattner G, Tignor M, Allen S, Boschung J, *et al.*: **Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change**. *Clim Change* 2013, **5**:1–1552.

75. Shen HZ, Chen YL, Hu YT, Ran LM, Lam SK, Pavur GK, *et al.*: **Intense warming will significantly increase cropland ammonia volatilization threatening food security and ecosystem health**. *One Earth* 2020, **3**:126–134.

76. Romer PS, Duffey KC, Wooldridge PJ, Edgerton E, Baumann K, Feiner PA, *et al.*: **Effects of temperature-dependent NO_x emissions on continental ozone production**. *Atmos Chem Phys* 2018, **18**:2601–2614.

77. Kou D, Yang GB, Li F, Feng XH, Zhang DY, Mao C, *et al.*: **Progressive nitrogen limitation across the Tibetan alpine permafrost region**. *Nat Commun* 2020:11.

78. Lacroix F, Zaehle S, Caldararu S, Schaller J, Stimmler P, Holl D, *et al.*: **Mismatch of N release from the permafrost and vegetative uptake opens pathways of increasing nitrous oxide emissions in the high Arctic**. *Global Change Biol* 2022, **28**: 5973–5990.

79. Ramm E, Liu CY, Ambus P, Butterbach-Bahl K, Hu B, Martikainen PJ, *et al.*: **A review of the importance of mineral nitrogen cycling in the plant-soil-microbe system of permafrost-affected soils-changing the paradigm**. *Environ Res Lett* 2022, **17**.

80. Mason RE, Craine JM, Lany NK, Jonard M, Ollinger SV, Groffman PM, *et al.*: **Evidence, causes, and consequences of declining nitrogen availability in terrestrial ecosystems**. *Science* 2022, **376**:261.

81. Tu XS, Wang J, Liu XY, Elrys AS, Cheng Y, Zhang JB, *et al.*: **Inhibition of elevated atmospheric carbon dioxide to soil gross nitrogen mineralization aggravated by warming in an agroecosystem**. *Environ Sci Technol* 2022, **56**:12745–12754.

82. Dove NC, Safford HD, Bohlman GN, Estes BL, Hart SC: **High-severity wildfire leads to multi-decadal impacts on soil biogeochemistry in mixed-conifer forests**. *Ecol Appl* 2020:30.

83. Li JQ, Pei JM, Liu JJ, Wu JH, Li B, Fang CM, *et al.*: **Spatiotemporal variability of fire effects on soil carbon and nitrogen: a global meta-analysis**. *Global Change Biol* 2021, **27**:4196–4206.

84. Perez-Quezada JF, Cano S, Ibaceta P, Aguilera-Riquelme D, Salazar O, Fuentes JP, *et al.*: **How do land cover changes affect carbon-nitrogen-phosphorus stocks and the greenhouse gas budget of ecosystems in southern Chile?** *Agric Ecosyst Environ* 2022:340.

85. Tian HQ, Bian ZH, Shi H, Qin XY, Pan NQ, Lu CQ, *et al.*: **History of anthropogenic Nitrogen inputs (HaNi) to the terrestrial biosphere: a 5 arcmin resolution annual dataset from 1860 to 2019**. *Earth Syst Sci Data* 2022, **14**:4551–4568.

86. Jensen ES, Carlsson G, Hauggaard-Nielsen H: *Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis.* Agronomy for Sustainable Development; 2020:40.

87. Fu YY, Li R, Huang JG, Bergeron Y, Fu YF, Wang Y, *et al.*: **Satellite-observed impacts of wildfires on regional atmosphere composition and the shortwave radiative forcing: a multiple case study**. *J Geophys Res Atmos* 2018, **123**:8326–8343.

88. Ward DS, Kloster S, Mahowald NM, Rogers BM, Randerson JT, Hess PG: **The changing radiative forcing of fires: global model estimates for past, present and future**. *Atmos Chem Phys* 2012, **12**:10857–10886.

89. Megaritis AG, Fountoukis C, Charalampidis PE, Pilinis C, Pandis SN: **Response of fine particulate matter concentrations to changes of emissions and temperature in Europe**. *Atmos Chem Phys* 2013, **13**:3423–3443.

90. Thornhill G, Collins W, Olivi D, Skeie RB, Archibald A, Bauer S, *et al.*: **Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models**. *Atmos Chem Phys* 2021, **21**: 1105–1126.

91. Finney DL, Doherty RM, Wild O, Stevenson DS, MacKenzie IA, Blyth AM: **A projected decrease in lightning under climate change**. *Nat Clim Change* 2018, **8**. 210-+.

92. Finney DL, Doherty RM, Wild O, Young PJ, Butler A: **Response of lightning NO_x emissions and ozone production to climate change: insights from the atmospheric chemistry and climate model intercomparison project**. *Geophys Res Lett* 2016, **43**:5492–5500.

93. Murray LT, Fiore AM, Shindell DT, Naik V, Horowitz LW: *Large uncertainties in global hydroxyl projections tied to fate of reactive nitrogen and carbon*. Proceedings of the National Academy of Sciences of the United States of America; 2021:118.

94. Zhao Y, Saunois M, Bousquet P, Lin X, Hegglin MI, Canadell JG, *et al.*: **Reconciling the bottom-up and top-down estimates of the methane chemical sink using multiple observations**. *Atmos Chem Phys* 2023, **23**:789–807.

95. Li ZL, Zeng ZQ, Tian DS, Wang JS, Fu Z, Zhang FY, *et al.*: **Global patterns and controlling factors of soil nitrification rate**. *Global Change Biol* 2020, **26**:4147–4157.

96. Chen TZ, Zhang P, Ma QX, Chu BW, Liu J, Ge YL, *et al.*: *Smog chamber study on the role of NOx in SOA and O3 formation from aromatic hydrocarbons*. Environmental Science & Technology; 2022.

97. Cho C, Fuchs H, Hofzumahaus A, Holland F, Bloss WJ, Bohn B, *et al.*: **Experimental chemical budgets of OH, HO2, and RO2 radicals in rural air in western Germany during the JULIAC campaign 2019**. *Atmos Chem Phys* 2023, **23**: 2003–2033.

98. Pimlott MA, Pope RJ, Kerridge BJ, Latter BG, Knappett DS, Heard DE, *et al.*: **Investigating the global OH radical distribution using steady-state approximations and satellite data**. *Atmos Chem Phys* 2022, **22**:10467–10488.

99. Zhang YZ, Jacob DJ, Maasakkers JD, Sulprizio MP, Sheng JX, Gautam R, *et al.*: **Monitoring global tropospheric OH concentrations using satellite observations of atmospheric methane**. *Atmos Chem Phys* 2018, **18**:15959–15973.

100. Lu XK, Vitousek PM, Mao QG, Gilliam FS, Luo YQ, Turner BL, *et al.*: *Nitrogen deposition accelerates soil carbon sequestration in tropical forests*. Proceedings of the National Academy of Sciences of the United States of America; 2021:118.

101. Voigt C, Marushchak ME, Abbott BW, Biasi C, Elberling B, Siciliano SD, *et al.*: **Nitrous oxide emissions from permafrost-affected soils**. *Nat Rev Earth Environ* 2020, **1**: 420–434.

102. Patil RH, Laegdsmand M, Olesen JE, Porter JR: **Effect of soil warming and rainfall patterns on soil N cycling in Northern Europe**. *Agric Ecosyst Environ* 2010, **139**:195–205.

103. Tymstra C, Stocks BJ, Cai XL, Flannigan MD: **Wildfire management in Canada: review, challenges and opportunities**. *Progress in Disaster Science* 2020, **5**.

104. You LC, Ros GH, Chen YL, Shao Q, Young MD, Zhang FS, *et al.*: **Global mean nitrogen recovery efficiency in croplands can be enhanced by optimal nutrient, crop and soil management practices**. *Nat Commun* 2023:14.

105. Kumar R, Mishra JS, Rao KK, Mondal S, Hazra KK, Choudhary JS, *et al.*: **Crop rotation and tillage management options for sustainable intensification of rice-fallow agroecosystem in eastern India**. *Sci Rep* 2020:10.

106. Venkatesh MS, Hazra KK, Ghosh PK, Khuswah BL, Ganeshamurthy AN, Ali M, *et al.*: **Long-term effect of crop rotation and nutrient management on soil-plant nutrient cycling and nutrient budgeting in Indo-Gangetic plains of India**. *Arch Agron Soil Sci* 2017, **63**:2007–2022.

107. Kattge J, Díaz S, Lavorel S, Prentice IC, Leadley P, Bönisch G, … Wirth C: **TRY – A global database of plant traits**. *Global Change Biology* 2011, **17**(9):2905–2935. https://doi.org/10.1111/j.1365-2486.2011.02451.x.